Ice clouds lidar ratio and multiple scattering factor in Version 4 CALIOP Level 2 algorithm

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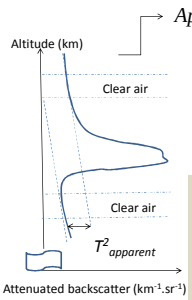
Extensive **combined analyses** of Version 3 perfectly collocated observations from **CALIOP and IIR**

IIR data selection: Single-layered semi-transparent cirrus clouds (Randomly oriented ice, high confidence), night, ocean.

CALIOP visible extinction optical depth: τ_{vis}



Apparent 2-way transmittance

$$T^2_{apparent} = e^{-2\tau_{app}}$$

$\tau_{vis} = \tau_{app} / \eta$

Apparent lidar ratio

$$S* = \frac{1 - T^2_{apparent}}{2\gamma'}$$

Lidar ratio: $S_c = S*/\eta$

γ': layer-integrated attenuated backscatter (sr^{-1})

η: multiple scattering factor

Version 3 summary:

- **Constrained retrievals** => 2-way transmittance can be measured and estimated uncertainty in derived S_c is smaller than 40%.
- **Unconstrained retrievals**: others, **default lidar ratio S_c=25 sr**.
- **Multiple scattering factor: η=0.6**

(Young and Vaughan, JAOT, 2009; Young et al, JAOT, 2013; Platt, JAS, 1973)

IIR absorption optical depth at 12.05 µm: τ_a

R_m: measured radiance — R_{ref}: reference radiance

$$\tau_a = -\ln(1-\varepsilon_{eff})$$

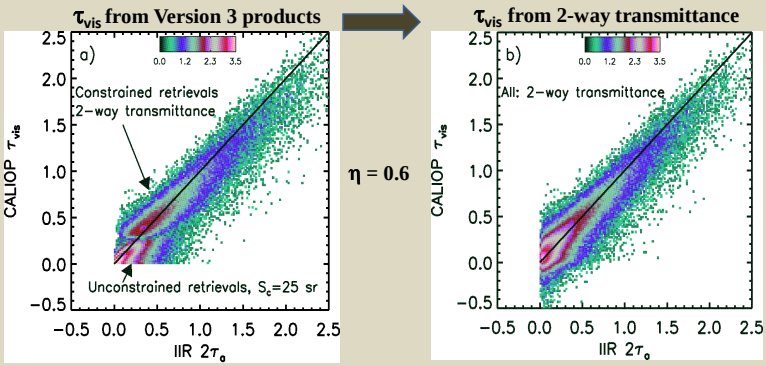
$$\varepsilon_{eff} = \frac{R_m - R_{ref}}{R_{BB} - R_{ref}}$$

R_{BB}: blackbody radiance, temperature T_r

- **τ_{vis}/τ_a ~2**; can be estimated in more details from theory and ice crystal effective diameters retrieved from IIR microphysical algorithm.
- **τ_a weakly sensitive to multiple scattering** (< 2%).
- T_r corrected a posteriori using CALIOP extinction profiles:
  => τ_a increased on average by 1% at $2\tau_a$ = 0.3 to 7% at $2\tau_a$ = 2.

(Platt, JAS, 1973; Garnier et al., JAMC, 2012; Garnier et al., AMT, 2015)

Lidar ratio

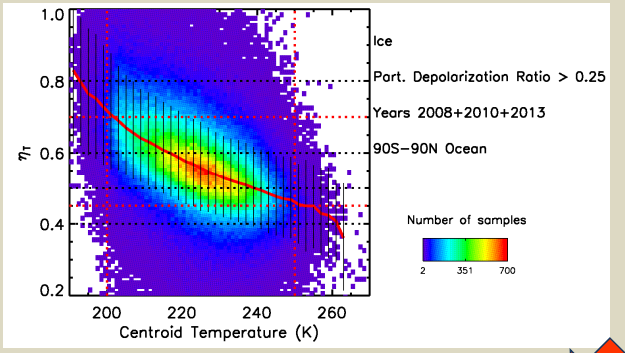


- **Discontinuity** between CALIOP constrained and unconstrained retrievals.
- Version 3 default lidar ratio S_c = 25 sr too small on average.
- Version 3 constrained retrievals: high bias at optical depth < 0.6 due to truncation of optical depth distributions (Garnier et al., AMT, 2015).

- **No discontinuity** in the comparisons.
- On average, CALIOP and IIR compare as expected (τ_{vis}/τ_a about 2).
- **Version 4 lidar ratio is derived from constrained retrievals.**
- **Version 4 constrained technique is extended to smaller optical depths, which will substantially increase the number of constrained retrievals (night & day).**

Multiple scattering factor

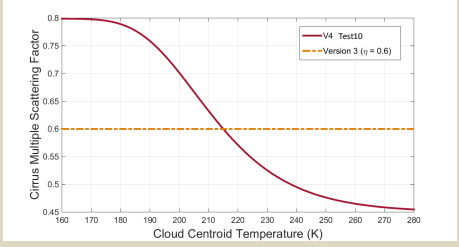
- The ratio τ_{vis}/τ_a, with τ_{vis} derived from the 2-way transmittance using η = 0.6, is found to vary with temperature and to be inconsistent with theory.
- A **temperature dependent** « bulk » **multiple scattering factor** η_T is derived by reconciling observed and expected τ_{vis}/τ_a ratios for $2\tau_a$ > 0.3 to minimize biases (Garnier et al., AMT, 2015).
- The theoretical τ_{vis}/τ_a ratios are obtained using the column_8_elements crystal model from Ping Yang (Yang et al., JAS, 2013).



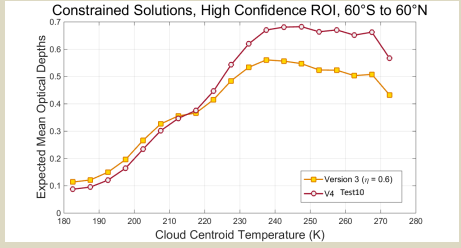
Version 4 cirrus multiple scattering factor and lidar ratio are parameterized as functions of temperature.

The default lidar ratios used in Version 4 unconstrained retrievals are derived based on statistics of Version 4 constrained retrievals at the same temperature.

Sigmoid approximation function for multiple scattering factor
Version 4 Test10
Version 3: η=0.6



Expected mean optical depths for Version 4 constrained solutions
Version 4 Test10
η=0.6



Sigmoid approximation function for lidar ratio in Version 4 Test10 compared to retrieved lidar ratios from constrained solutions and opaque layers